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Reduced exposure to coughed air by a novel ventilation method for hospital patient rooms

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Abstract

A novel hospital bed integrated ventilation and cleaning unit (HBIVCU) for local airflow control and cleansing, limiting the airborne spread of contagious air coughed from a sick patient in a hospital room, was developed. The performance efficiency of the unit, to successfully reduce occupants' exposure to coughed air, was studied in a full-scale, two-bed hospital room mock-up, 4.65 m x 4.65 m x 2.60 m (W x L x H), with two patients and a doctor. Four units were placed along the two sides of both beds close to the head. The room was ventilated by overhead mixing air distribution at 22 ^{o}C room air temperature. The sick coughing patient was simulated by a heated dummy with simplified geometry equipped with a cough generator. Similar heated dummy was used for the second patient. A dressed breathing thermal manikin with realistic human body and surface temperature was used to mimic a doctor standing beside the bed and facing the coughing patient. The generated cough consisted of 100% CO_2. The mouth was simulated by a circular opening of 0.021 m diameter. The characteristics of the cough were: peak flow - 10 L/s, cough volume - 2.5 L, duration - 0.5 s and maximum velocity - 28.9 m/s. The performance of the novel unit, at background ventilation rates of 3 $h^{-1}$and 6 h^{-1}, was evaluated by measuring the excess CO_2 concentration at the mouth of both the doctor and the exposed patient. When the novel method was not used, the CO_2 concentration (exposure) measured in the air "inhaled" by the doctor exceeded 20 times the background CO_2 level and more than 12 times for the exposed patient. No increase in the CO_2 concentration in inhalation was measured for either the doctor or the second patient, when the HBIVCUs were operational.

Key words: Hospital Ventilation, local control, cough, exposure, concentration, physical measurements, tracer gas, HBIVCU.

1. Introduction

Ventilation aims to provide occupants with fresh and healthy, free from hazardous matter and contagious pathogens air for breathing, as well as comfortable thermal environment. However the existing ventilation strategies of hospital rooms, namely mixing and displacement air distribution, fail to fulfill these goals (Kao and Yang 2006, Qian et al. 2006, Noakes et al. 2009, Tung et al. 2009). Their weak points are especially noted today with the rise of new/mutated pathogens responsible for epidemics and pandemics outbreaks, such as the *SARS*, *H5N1* and *H1N1* viruses. In rooms with mixing air distribution all occupants are equally exposed to airborne pathogens provided good mixing is achieved. Persons with weaker immune system like children, elderly or immune-compromised are under elevated risk from airborne cross infection. Therefore high ventilation air change rates are recommended, e.g. minimum of 12 air change rates per hour (ACH) are required for ventilation of infectious hospital wards and 6 for normal patient rooms (ASHRAE 170 2008, CDC guidelines 2005, DS 2451-9 Dansk standard 2003). Full-scale experiments reveal that medical staff and patients are exposed to air coughed by a sick patient even at 12 ACH (Bolashikov et al. 2010, Klerat et al. 2010).

The displacement air distribution also has its weak points, namely it is very sensitive to movement of people or other moving objects as the supply velocities are quite low (Halvoňová and Melikov 2010). Displacement ventilation can affect the exhaled air propagation horizontally, by "locking" it between the stratified layers formed as a result of the temperature gradient (Qian et al. 2006, Bolashikov et al. 2012). Hence, the displacement ventilation can increase the risk from cross-infection from airborne transmission between occupants, provided the stratification zone is within the breathing zone of the sick occupant.

Everyday pulmonary activities, like breathing, coughing, sneezing, talking or even singing, are source of droplets (Cole and Cook 1998, Edwards et al. 2004, Wong and Leung 2004). These human generated aerosols can be laden with microorganisms and/or viruses if the person is sick. After leaving “the host”, the droplets are transported by the ambient air. Their fate depends on the droplet properties, the environmental conditions as well as the flow interaction within the vicinity of every occupant. This interaction is dominated by many factors such as the nature of the airflow generated (coughing, sneezing, breathing etc.), the natural convection surrounding the human body, the presence of any source of forced convection within the occupied zone, the background ventilation, the use of personalized ventilation, etc. Although important, not much knowledge is available on the flow interaction within the occupied zone especially near the breathing zone of an occupant, and clearly more understanding is needed (Bolashikov and Melikov 2009).

The existing ventilation strategies and technologies rely solely on dilution by supplying large amounts of conditioned clean air. This makes them energy inefficient and demanding. In many cases the ventilation systems create problems connected with elevated velocities and draught issues due to increased flow rates of air. New ways of ventilation design within the occupied zone are required, that will introduce control over the flow interaction locally and will reduce the exposure to and spread of human generated contagious aerosols indoors. These new advanced air distribution techniques should be able to meet the requirements of all occupants for air quality and thermal comfort, and reduce the exposure to indoor pollutants and health hazardous matter (i.e. toxic chemicals, contagious microorganisms/viruses, allergens etc.). At the same time these new ventilation strategies should be user friendly and energy efficient and result in increased well-being and self-performance of the end users.

2. Method

Experiments were designed and performed in a full-scale experimental room with dimensions 4.65 m x 4.65 m x 2.60 m (W x L x H) furnished to simulate a hospital isolation room with two beds. The distance between the beds was set to 1.3 m. Five ceiling-mounted light fixtures (6 W each) provided the background lighting. The room was located in a tall hall, where the temperature was kept constant and equal to the air temperature in the test room. A heated dummy (60 W) with simplified body geometry, equipped with a coughing machine was used to simulate the coughing sick patient lying in one of the beds. The mouth of the coughing patient was a circular opening (diameter of 0.021 m). The characteristics of the cough were: volume peak flow - 10 L/s, volume of the cough - 2.5 L, cough time interval - 0.5 s, maximum velocity - 28.9 m/s. A second heated dummy (60 W) was used to simulate a patient lying in the other bed aligned with the bed of the coughing patient. A dressed breathing thermal manikin with realistic human body size, shape and surface temperature distribution was used to resemble a “doctor”. Under the studied conditions the whole body heat loss from the manikin corresponded to 60 W of sensible heat load. The layout of the set-up is shown in Figure 1.

Mixing type of air distribution was used to condition the air in the room. The air supply diffuser (a four way diffuser) and two air exhausts (a perforated square diffusers mounted above the heads of every patient) were installed on the ceiling. The exhaust air was equally balanced between the two outlets. The supplied air was 100% outdoor (no recirculation was used). A slight under-pressure of 1.6±0.2 Pa was kept during all the experiments in order to avoid leaking of air from the test room into the tall hall. The supply air temperature and the air flow supplied and exhausted were continuously controlled to keep the set values as defined for each of the tested conditions.

Four devices named Hospital Bed Integrated Ventilation Cleansing Unit (HBIVCU), one at each side of each bed, were used in the experiment. At present the unit is a subject of patent approval in Europe (EP 09165736.1) and USA (US 61/226,542). Briefly stated, the HBIVCU is box shaped with dimensions of 0.6 m x 0.145 m x 0.60 m (L x W x D). It can be installed at either sides and/or head of a bed. HBIVCU helps to exhaust the air from the pulmonary activities of the sick occupant/patient (breathing, coughing, sneezing etc.), clean that air from the pathogens via UVC light and then discharges it vertically through a horizontal slot, at a high initial momentum towards the ceiling where it is to be exhausted by the total volume ventilation. For the purpose of the present experiments two slots were made on the device: suction opening (0.50 m x 0.14 m, L x W): sideways on the larger wall of the box, and a discharge opening (0.54 m x 0.05 m, L x W) on the top (Figure 1). It is important to note that in some applications the suction can be used as a supply and the discharge opening as an exhaust opening (not reported here). For the purpose of this study a separate HVAC system was assigned to supply air isothermally to the discharge section of the box and to exhaust the air from the local suction of the box. The amount of air supplied and exhausted was always the same and was determined by the initial discharge velocity from the top slot (1.4 m/s, corresponding to 36.8 L/s). The experiments were performed with either 2 pairs of HBIVCUs installed (one at each side of the two beds) or without any device at all – reference case.

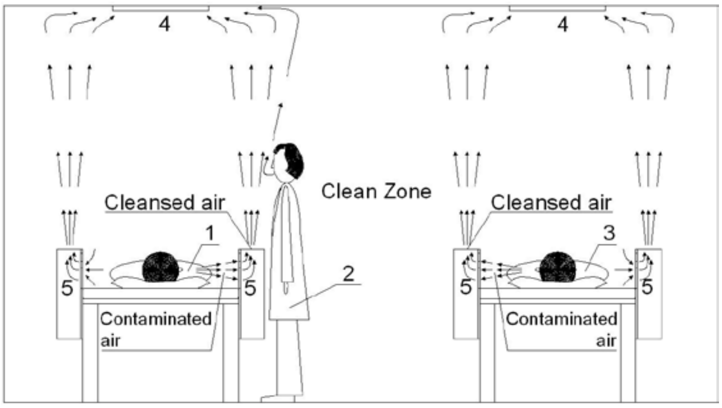


Figure 1. Air distribution in a room with the HBIVCU (Hospital Bed Integrated Ventilation Cleansing Unit). Sick patient (1),(3) coughing or breathing sideways. The doctor (2) is sealed within the clean zone by the air curtains created by the HBIVCU (5). The contaminated air is cleansed and directed upwards towards the ceiling to the total volume ventilation exhaust (4).

Experiments were performed at two air-change rates: 3 and 6 h^{-1} with and without the HBIVCUs. Room temperature was kept at 22˚C while the relative humidity was not controlled. The coughed flow was 100% CO_2. The CO_2 concentration at the mouth of the doctor and the second patient was measured with specially developed instrument with time constant of 0.8 s and sampling rate of 4 Hz. CO_2 concentration measurements at the supply, exhaust and several points in the occupied zone were performed as well using multi-gas analyzer based on the photo-acoustic principle to keep track on the background concentration.

For each of the studied conditions 15 to 20 repeated measurements of simulated cough were collected and averaged. Special software was prepared and used for the processing of the measured data. All results are presented as excess CO_2 concentration above the room level for each of the studied two different air change rates.

Two more parameters are discussed in the following, namely the Pick Concentration Level (PCL) and the Peak Concentration Time (PCT). PCL is defined as the maximum concentration measured at the mouth of the doctor or the second patient shortly after the cough was generated; PCT is defined as the time at which the PCL is reached (Melikov et al. 2009).

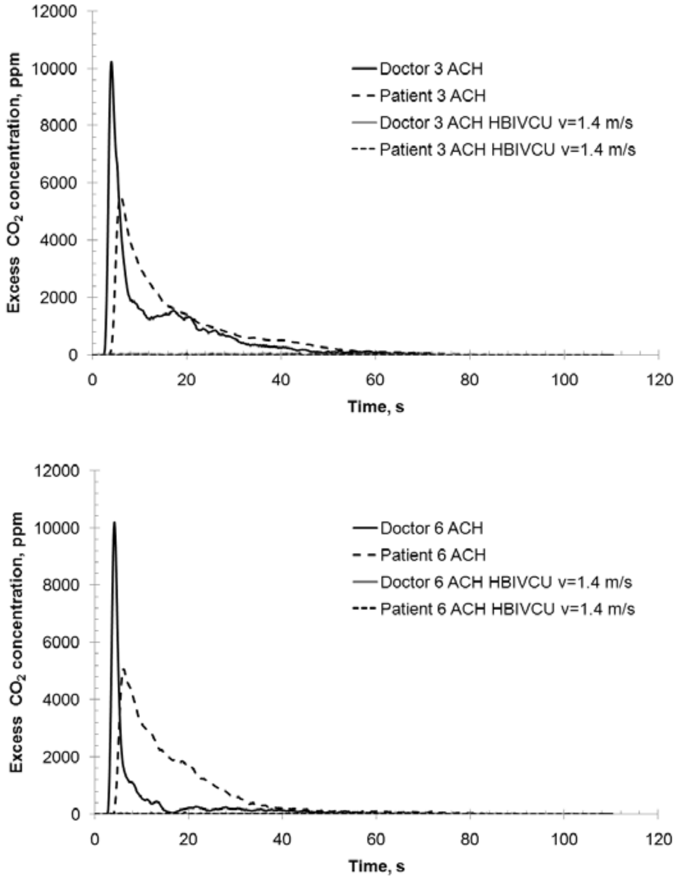
Several experiments were performed to study the exposure to exhaled air for the doctor standing and facing the coughing patient at a distance of 0.55 m and for the second exposed patient, with: a) the HBIVCU as an obstacle (when it was present but not in operational); b) the HBIVCU operated at different discharge velocity, and c) the HBIVCU operated under different background ventilation rates. The current paper presents the impact of the background ventilation rate only, performed at 3 and 6 h^{-1} respectively.

3. Results and Discussion

The excess CO_2 concentration sampled at the mouth of the doctor and the exposed patient at 3 and 6 h^{-1} with and without HBIVCUs installed after single cough is shown in Figure 2. The results in the figure reveal that without HBIVCU, the CO_2 concentration for both the doctor and the second patient increased dramatically just after the cough. The difference in excess CO_2 concentration under 3 and 6 h^{-1} was small. The use of the HBIVUC protected the doctor and the second patient from the coughed air, by successfully exhausting it locally.

Figure 2 clearly demonstrates that the efficiency of the HBIVCU in protecting the doctor and the second patient from the air coughed by the sick it may be expected that even at 12 h^{-1} the use of the HBIVCU units will be effective and not affected.

The measured PCT was shorter for the doctor (≈ 2.5 s) and almost doubled for the exposed patient (≈ 4 s), when the novel ventilation method (HBIVCU) was not used. When the HBIVCUs were installed at each bed, the PCT could not be identified for both the doctor and the exposed patient. All of the exhaled air was successfully captured by the exhaust opening of the unit.



a)

b)

Figure 2. CO2 concentration change in time at the mouth of the "doctor" standing at distance of 0.55 m from the coughing patient and at the mouth of the exposed patient in the second bed (1.3 m away). The coughing patient lies on its side and is facing the doctor and the second patient. The results obtained with the HBIVCU at discharge velocity of 1.4 m/s and at the reference case without HBIVCU are compared for a) 3 h^{-1} and b) 6 h^{-1}.

patient was not influenced by the total volume ventilation in the room, when the background ventilation rate was increased from 3 to 6 h^{-1}. The PCL measured, never rose above the background CO_2 level, when the HBIVCU was operated at 1.4 m/s. The relatively close distance between the mouth of the sick coughing patient and the suction opening of the unit resulted in efficient evacuation of the contagious exhaled air. Based on these results

The studied novel method for reducing the spread and mixing of the coughed air with the room air in hospital room, proved to be efficient in evacuating the coughed air from a sick patient, and provide protection for both medical staff and roommate patients. A ventilation unit in close proximity with the mouth of a sick person guarantees the successful evacuation of the largest part of the contagious air generated from pulmonary activities. The captured air after being purged (via UVGI or another cleaning method) is directed upwards at elevated velocities, through one or more horizontal slots, towards the exhaust vents of the total volume ventilation (Figure 1). Thus the directed upwards cleansed air would act as a barrier between the medical staff member staying close to the bed from one side and the patient on the other side. The discharged air jets (acting as air curtains) will entrain any “escaped” coughed air and will move it also upward towards the background ventilation exhaust. Another possibility is to connect the HBIVCU via flexible duct to the total volume (TV) ventilation exhaust and extract the pathogen laden air out of the room, or with the TV supply to provide clean air into the room from the horizontal slots. The compatibility of the unit would make it quite flexible from energy point of view: it could even be powered by battery unit or plugged into the mains. The expectation is that the unit would have some potential for energy savings. The local extraction of air expelled by the sick individual will lead to reduction in the amount of air from the total volume ventilation: less air will be needed for dilution. Thus less air would be conditioned and will be supplied indoors. The idea is that the device is mobile and easily transported and mounted on the patients’ beds. Its present design follows the new concept for hospital appliances and furniture, namely “plug and operate”. The benefits of introducing the HBIVCU unit into conventional hospital rooms are obvious: a healthier working environment for the medical staff and faster recovery for all patients with reduced risk from nosocomial infections and secondly the potential for energy savings and flexibility of hospital space (no special infectious wards will be needed).

4. Conclusions

A novel ventilation method, named HBIVCU, for reducing the risk from airborne cross-infection in infectious hospital wards was studied in a full-scale mock-up simulating a hospital room with two patients and a doctor. The following conclusions are made:

- The use of the HBIVCU acts as an efficient means to reduce the exposure to coughed air of people standing closely to the bed of a coughing sick patient. Based on this results it can be suggested that the risk of airborne cross-infection can be significantly reduced when the novel method for local ventilation is implemented;
- The performance of the HBIVCU for the studied conditions is unaffected by the rate of the background ventilation flow (studied up to 6 h^{-1});
- The use of the HBIVCU unit in conjunction with total volume mixing air distribution may lead to substantial lowering of the background ventilation rate and thus to possible energy saving.

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